UNITED STATES PATENT APPLICATION

TITLE: POWER CYCLE AND SYSTEM FOR UTILIZING MODERATE AND LOW TEMPERATURE HEAT SOURCES

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RELATED APPLICATIONS

[0001] This application is a Continuation-in-Part of United States Patent Application Serial No. 10/357,328 filed 3 February 2003.

BACKGROUND OF THE INVENTION

1. **Field of the Invention**

[0002] The present invention relates to a system and method for the utilization of heat sources with moderate to low initial temperature, such as geothermal waste heat sources or other similar sources.

[0003] More particularly, the present invention relates to a system and method for the utilization of heat sources with moderate to low initial temperature, such as geothermal waste heat sources or other similar sources involving a multi-staged heating process and at least one separation step to enrich the working fluid which is eventually fully vaporized for energy extraction.

2. **Description of the Related Art**

[0004] In the prior art, US patent number 4982568, a working fluid is a mixture of at least two components with different boiling temperatures. The high pressure at which this working fluid vaporizes and the pressure of the spent working fluid (after expansion in a turbine) at which the working fluid condenses are chosen in such a way that at the initial temperature of condensation is higher than the initial temperature of boiling. Therefore, it is possible that the initial boiling of the working fluid is achieved by recuperation of heat released in the process of the condensation of the spent working fluid. But in a case where the initial temperature of the heat source used is moderate or low, the range of temperatures of the heat source is narrow, and therefore, the possible range of such recuperative boiling-condensation is significantly reduced and the efficiency of the system described in the prior art diminishes.

[0005] Thus, there is a need in the art for a new thermodynamic cycle and a system based thereon for enhanced energy utilization and conversion.

SUMMARY OF THE INVENTION

[0006] The present invention provides a method for extracting thermal energy from low to moderate

temperatures source streams including the step of transforming thermal energy from a fully vaporized boiling stream into a usable energy form to produce a lower pressure, spent stream. The fully vaporized boiling stream is formed by transferring thermal energy from an external heat source stream to a boiling stream to form the fully vaporized boiling stream and a cooled external heat source stream. The method also includes the steps of transferring thermal energy from the spent stream to a first portion of a heated higher pressure, basic working fluid stream to form a partially condensed spent stream and a first pre-heated, higher pressure, basic working fluid stream and transferring thermal energy from the cooled external heat source stream to a second portion of the heated higher pressure, basic working fluid stream to form a second pre-heated, higher pressure, basic working fluid stream and a spent external heat source stream. The method also includes the steps of combining the first and second pre-heated, higher pressure basic working fluid streams to form a combined pre-heated, higher pressure basic working fluid stream and separating the partially condensed spent stream into a separated vapor stream and a separated liquid stream. The method also includes the steps of pressurizing a first portion of the separated liquid stream to a pressure equal to a pressure of the combined pre-heated, higher pressure basic working fluid stream to form a pressurized liquid stream and combining the pressurized liquid stream with the combined pre-heated, higher pressure basic working fluid stream to form the boiling stream. . The method also includes the steps of combining a second portion of the separated liquid stream with the separated vapor stream to from a lower pressure, basic working fluid stream and transferring thermal energy from the lower pressure, basic working fluid stream to a higher pressure, basic working fluid stream to form the heated, higher pressure, basic working fluid stream and a cooled, lower pressure, basic working fluid stream. The method also includes the steps of transferring thermal energy cooled, lower pressure, basic working fluid stream to an external coolant stream to from a spent coolant stream and a fully condensed, lower pressure, basic working fluid stream; and pressurizing the fully condensed, lower pressure, basic working fluid stream to the higher pressure, basic working fluid stream.

[0007] In a more efficient implementation of the present invention, the method provides the additional steps of separating the boiling stream into a vapor stream and a liquid stream; combining a portion of the liquid stream with the vapor stream and passing it through a small heater exchanger in contact with the external heat source stream to insure complete vaporization and superheating of the boiling stream. A second portion of the liquid stream is depressurized to a pressure equal to a pressure of the spent stream.

[0008] In a more yet more efficient implementation of the present invention, the method provides in addition to the additional steps described in paragraph **0006**, the steps of separating the depressurized second portion of the liquid stream of paragraph **0006** into a vapor stream and a liquid stream, where the vapor stream is combined with the pressurized liquid stream having the parameters of the point **9** and repressurized before being combined with the stream having the parameters of the point **8**. While the liquid stream is depressurized to a pressure equal to a pressure of the spent stream having the parameters of the point **18**.

[0009] The present invention provides a systems as set forth in Figures 1A-C adapted to implement the methods of this invention.

DESCRIPTION OF THE DRAWINGS

[00010] The invention can be better understood with reference to the following detailed description together with the appended illustrative drawings in which like elements are numbered the same:

[0011] Figure 1A depicts a schematic of a preferred thermodynamic cycle of this invention;

[0012] Figure 1B depicts a schematic of another preferred thermodynamic cycle of this invention;

[0013] Figure 1C depicts a schematic of another preferred thermodynamic cycle of this invention; and

[0014] Figure 1D depicts a schematic of another preferred thermodynamic cycle of this invention.

DETAILED DESCRIPTION OF THE INVENTION

[0015] he inventors have found that a novel thermodynamical cycle (system and process) can be implemented using a working fluid including a mixture of at least two components. The preferred working fluid being a water-ammonia mixture, though other mixtures, such as mixtures of hydrocarbons and/or freons can be used with practically the same results. The systems and methods of this invention are more efficient for converting heat from relatively low temperature fluid such as geothermal source fluids into a useful form of energy. The systems use a multi-component basic working fluid to extract energy from one or more (at least one) geothermal source streams in one or more (at least one) heat exchangers or heat exchange zones. The heat exchanged basic working fluid then transfers its gained thermal energy to a turbine (or other system for extracting thermal energy from a vapor stream and converting the thermal energy into mechanical and/or electrical energy) and the turbine converts the gained thermal energy into mechanical energy and/or electrical energy. The systems also include pumps to increase the pressure of the streams at certain points in the systems and a heat exchangers which bring the basic working fluid in heat exchange

relationships with a cool stream. One novel feature of the systems and methods of this invention, and one of the features that increases the efficiency of the systems, is the result of using a split two circuit design having a higher pressure circuit and a lower pressure circuit and where a stream comprising spent liquid separated for spent vapor from the higher pressure circuit is combined with a stream comprising the spent lower pressure stream at the pressure of the spent lower pressure stream prior to condensation to from the initial fully condensed liquid stream and where the combined stream is leaner than the initial fully condensed liquid stream. The present system is well suited for small and medium signed power units such as 3 to 5 Mega Watt power facilities.

[0016] The working fluid used in the systems of this inventions preferably is a multi-component fluid that comprises a lower boiling point component fluid – the low-boiling component – and a higher boiling point component – the high-boiling component. Preferred working fluids include an ammonia-water mixture, a mixture of two or more hydrocarbons, a mixture of two or more freon, a mixture of hydrocarbons and freon, or the like. In general, the fluid can comprise mixtures of any number of compounds with favorable thermodynamic characteristics and solubility. In a particularly preferred embodiment, the fluid comprises a mixture of water and ammonia.

[0017] It should be recognized by an ordinary artisan that at those point in the systems of this invention were a stream is split into two or more sub-streams, the valves that effect such stream splitting are well known in the art and can be manually adjustable or are dynamically adjustable so that the splitting achieves the desired improvement in efficiency.

[0018] Referring now to Figure 1A, a preferred embodiment of a system of this invention, generally **100**, is shown. The system **100** is described in terms of its operation using streams, conditions at points in the system, and equipment. A fully condensed working fluid stream at a temperature close to ambient having parameters as at a point **1**, enters a feed pump **P1**, where it is pumped to an elevated pressure, and obtains parameters as at a point **2**. The composition of the working fluid stream having the parameters of the point **2** will be hereafter referred to as a "basic composition" or "basic solution." The working fluid stream having the parameters of the point **2**, then passes through a recuperative pre-heater or heat exchanger **HE2**, where it is heated in counter flow by a returning stream of the basic solution as described below, and obtains parameters as at a point **3**. The state of the basic working solution at the point **3** corresponds to a state of saturated, or slightly sub-cooled liquid.

[0019] Thereafter, the stream of basic solution having the parameters of the point **3** is divided into two sub-streams having parameters as at points **4** and **5**, respectively. The sub-stream having the

parameters of the point **4**, then passes through a heat exchanger **HE4**, where it is heated and partially vaporized by a stream of a heat source fluid (*e.g.*, geothermal brine stream) having parameters as at a point **42** as described below, and obtains parameters as at a point **6**. While, the stream of basic solution having the parameters of the point **5** passes though a heat exchanger **HE3**, where it is heated and partially vaporized by a condensing stream having parameters as at a point **20** in a condensing process **20-21** also described below and obtains parameters as at a point 7. Thereafter, the sub-streams having parameters as at points **6** and **7** are combined, forming a combined stream having parameters as at a point **8**. The stream of basic solution having the parameters of the point **8** is then combined with a stream of a recirculating solution having parameters as at a point **29** as described below, and forms a stream of a boiling solution having parameters as at a point **10**. The stream having the parameters of the point **29** is in a state of sub-cooled liquid, and, therefore, as a result of the mixing of the streams having the parameters of the points **8** and **29**, a substantial absorption of vapor occurs, and the temperature rises substantially. Thus, a temperature of the stream having the parameters of the point **10** is usually significantly higher than that of the stream having the parameters of the point **8**. The composition of the stream having the parameters of the point **10** is referred to herein as a "boiling solution."

[0020] The stream of boiling solution having the parameters of the point **10**, then passes through a heat exchanger **HE5**, where it is heated and vaporized by the stream of the heat source fluid having parameters as at a point **41**. The vaporized stream exiting the heat exchanger **HE5** now has parameters as at a point **11**. The stream having the parameters of the point **11** then enters into a gravity separator **S2**, where it is separated into a vapor stream having parameters as at a point **13** and a liquid stream having parameters as at a point **12**. The liquid stream having the parameters of the point **12** is then divided into two sub-streams having parameters as at points **14** and **15**, respectively. The sub-stream having the parameters of the point **14** usually represents a very small portion of the total liquid stream, and is combined with the vapor stream having the parameters of the point **13** as described below, forming a stream of working solution with parameters as at a point **16**. The stream of working solution having the parameters of the point **16**, then passes through a heat exchanger **HE6** (a small heat exchanger sometimes called a vapor drier to insure that the state of the stream exiting the heat exchanger is a superheated vapor), where it is further heated by the stream of the heat source fluid having parameters as at a point **40**, to form a fully vaporized and slightly superheated stream having parameters as at a point **17**. Thereafter, the stream of working solution having the parameters of the point **17** passes through a turbine **T1**, where it is expanded, producing

useful power (conversion of thermal energy into mechanical and electrical energy) to form a stream having parameters as at a point **18**.

[0021] The recirculating liquid having the parameters of the point **15** as described above passes through a throttle valve **TV1**, where its pressure is reduce to an intermediate pressure to form a stream having parameters as at a point **19**. As a result of throttling, the parameters of the stream at the point **19** correspond to a state of a vapor-liquid mixture. The stream having the parameters of the point **19**, then enters into a gravity separator **S3**, where it is separated into a vapor stream having parameters as at the point **30**, and a liquid stream having parameters as at a point **31**. The liquid stream having the parameters of the point **31** passes through a second throttle valve **TV2**, where its pressure is further reduced to a pressure to form a stream having parameters as at a point **32**, where the pressure of the stream having the parameters of the point **32** is equal to a pressure of the stream having the parameters of the point **18** as described above. Thereafter, the stream having the parameter of the point **32** and the stream having the parameters of the point **18** are combined forming a stream of a condensing solution having the parameters of the point **20**. The stream having parameters of the point **20** passes through the heat exchanger **HE3**, in counter flow to the stream having the parameters of the point **5**, in a cooling process **5-7**. After passing through the heat exchanger **HE3**, the stream having the parameters of the point 20 is partially condensed, releasing heat for the heating process **20-21** described above and obtains parameters as at a point **21**.

[0022] The stream having the parameters of the point **21** then enters into a gravity separator **S1**, where it is separated into a vapor stream having parameters as at a point **22** and a liquid stream having parameters as at a point **23**. The liquid stream having the parameters of the point **23** is in turn divided into two sub-streams having parameters as at points **25** and **24**, respectively. The liquid sub-stream having the parameters of the point **25** is then combined with the vapor stream having the parameters of the point **22**, forming a stream of the basic solution having parameters as at a point **26**.

[0023] The liquid sub-stream having parameters of the point **24** enters a circulating pump **P2**, where its pressure is increased to a pressure equal to a pressure in gravity separator S3, *i.e.*, equal to a pressure of the vapor stream having the parameters of the point **30** described above, and obtains parameters as at point **9**. The liquid stream having the parameters of the point **9** is in a state of a sub-cooled liquid. The liquid stream having the parameters of point **9** is then combined with the vapor stream having the parameters of the point **30** described above. A pressure of the streams having tje parameters of the points **9** and **30** is chosen in such a way that the sub-cooled liquid having the

parameters of the point **9** fully absorbs all of the vapor stream having the parameters of the point **30**, forming a liquid stream having parameters as at point **28**. The liquid stream having the parameters of the point **28** is in a state of saturated or sub-cooled liquid. Thereafter, the stream having the parameters of the point **28** enters into a circulating pump **P3**, where its pressure is increased to a pressure equal to a pressure of the stream having the parameters of the point **8**, and obtains parameters of the point **29** described above. The stream having the parameters of the point **29** is then combined with the stream of basic solution having the parameters of the point **8**, forming the stream of the boiling solution having the parameters of the point **10** described above.

[0024] The stream of basic solution having the parameters of the point **26** enters into the heat exchanger **HE2**, where it partially condenses releasing heat for a heating process **2-3** described above, and obtains parameters as at a point **27**. Thereafter the stream of basic solution having the parameters of the point **27** enters into a condenser **HE1**, where its is cooled and fully condensed by an air or water stream having parameters as at point **51** described below, and obtains parameters of the point **1**.

[0025] An air (or water) stream having parameters as at a point **50** enters an air fan **AF** (or compressor in the case of water) to produce an air stream having parameters as at a point **51**, which forces the air stream having the parameters of the point **51** into the heat exchanger **HE1**, where it cools the stream of basic working fluid in a cooling process **27-1**, and obtains parameters as at point **52**.

[0026] The stream of heat source fluid with the parameters of the point **40** passes through the heat exchanger **HE6**, where it provides heat from a heating process **6-17**, and obtains the parameters of the point **41**. The stream of heat source fluid having the parameters of the point **41** passes through the heat exchanger **HE5**, where it provides heat for a heating process **10-11**, and obtains the parameters of the point **42**. The stream of heat source fluid having the parameters of the point **42** enters into the heat exchanger **HE4**, where it provides heat for a heating process **4-6** and obtains parameters as at point **43**.

[0027] In the previous variants of the systems of this invention, the recirculating stream having parameters as at the point **29** was mixed with the stream of basic solution having parameters as at the point **8**. As a result of this mixing, a temperature of the combined stream having parameters as at the point **10** was substantially higher than a temperature of the streams having parameters as at the points **8** and **29**.

[0028] Referring now to **Figure 1D**, another embodiment of the system of this invention, generally

100, is shown to includes an additional heat exchanger **HE7**, *i.e.*, the heat exchanger **HE5** is split into two heat exchangers **HE5'** and **HE7** designed to reduce the temperature difference between the stream, having the parameters as at the point **10** and the streams having the parameters as at the points **8** and **29**.

[0029] In the new embodiment, the stream with parameters as at the point **8** is sent into the heat exchanger **HE7** where it is heated and further vaporized by a heat source stream, such as a geothermal fluid stream, having the parameters as at a point **44** producing the heat source stream having parameters as at the point **42** in a counter flow heat exchange process **44-42** and a stream having parameters as at a point **34**. Only then is the steam having the parameters as at the point **34** mixed with a recircu1ating stream having the parameters as at the point **29** (as described above) forming a combined stream having parameters as at the point **10**. A temperature at of the stream having the parameters as at the point **34** is chosen in such a way that the temperature of the stream having the parameters as at the point **10** is equal or very close to the temperature of the stream having the parameters as at the point **34**. Asa result, the irreversibility of mixing a stream of basic solution and a stream of recirculating solution is drastically reduced. The resulting stream having the parameters as at the point **10** passes through the heat exchanger **HE5'** where it is heated and vaporized in a counter flow process **41-44** by the heat source stream such as a geothermal fluid stream having the parameters as at the point **41**.

[0030] This embodiment c an a lso i nclude a s ub-streams h aving p arameter a s a t p oints **1 4**, a s described above, which usually represents a very small portion of the total liquid stream, and is combined with the vapor stream having the parameters of the point **13** (not shown) as described below, to form the stream of working solution with parameters as at the point **16**. Additionally, this embodiment can also include the **AF** unit and associated streams as described above.

[0031] The advantages of the arrangement of streams shown in the present embodiment include at least the following: a temperature difference in the heat exchanger **HE7** (which is, in essence, the low temperature portion of the heat exchanger **HE5** in the previous variants), are substantially increased and therefore the size of the heat exchanger **HE7** is reduced, while the heat exchanger **HE5'** of this embodiment works in absolutely the same way as the high temperature portion of the heat exchanger **HE5** of the previous variants. The efficiency of the system of this embodiment is not affected at all.

[0032] This embodiment of the method of mixing a recirculating stream with a stream of basic solution can be applied to all variants described above. One experienced in the art can easily apply

this method without further explanation.

[0033] An example of calculated parameters for the points described above are given in Table 1 for the embodiment shown in Figure 1A.

TABLE 1
Parameter of Points in the Embodiment of Figure 1A

Point No.	Concentration X	Temperature T (°F)	Pressure P (psia)	Enthalpy h (btu/lb)	Enthropy S(btu/lb°F)	Weight (g/g1)
Parameters of Working Fluid Streams						
1	0.975	73.5	133.4091	37.8369	0.09067	1.0
2	0.975	75.0186	520.0	40.1124	0.09145	1.0
3	0.975	165.0	508.2780	147.9816	0.27769	1.0
4	0.975	165.0	508.2780	147.9816	0.27769	0.6010
5	0.975	165.0	508.2780	147.9816	0.27769	0.3990
6	0.975	208.0	498.5	579.1307	0.96196	0.6010
7	0.975	208.0	498.5	579.1307	0.96196	0.3990
8	0.975	208.0	498.5	579.1307	0.96196	1.0
9	0.40874	170.2394	220.0	45.8581	0.21737	0.3880
10	0.81773	231.1316	498.5	433.8631	0.76290	1.40575
11	0.81773	300.0	490.0	640.0316	1.04815	1.40757
12	0.35855	300.0	490.0	200.2510	0.43550	0.1950
13	0.89168	300.0	490.0	710.8612	1.14682	1.21075
14	0.35855	300.0	490.0	200.2510	0.43550	0.1655
15	0.35855	300.0	490.0	200.2510	0.43550	0.17845
16	0.8845	300.0	490.0	703.9808	1.13724	1.2272
17	0.8845	306.0	488.5	718.3184	1.15637	1.2273
18	0.8845	213.3496	139.5	642.4511	1.17954	1.2273
19	0.35855	249.1433	220.0	200.2510	0.44140	0.17845
20	0.81671	214.6540	139.5	584.8515	1.08437	1.3880
21	0.81671	170.0	137.5	460.9041	0.89583	1.3880

Point No.	Concentration X	Temperature T (°F)	Pressure P (psia)	Enthalpy h (btu/lb)	Enthropy S(btu/lb°F)	Weight (g/g1)
22	0.97746	170.0	137.5	624.6175	1.16325	0.99567
23	0.40874	170.0	137.5	45.4163	0.21715	0.39233
24	0.40874	170.0	137.5	45.4163	0.21715	0.3880
25	0.40874	170.0	137.5	45.4163	0.21715	0.00433
26	0.975	170.0	137.5	622.1123	1.15916	1.0
27	0.975	93.9659	135.5	514.2431	0.97796	1.0
28	0.43013	195.9556	220.0	74.5165	0.26271	0.40575
29	0.43013	196.6491	498.5	75.8407	0.26312	0.40575
30	0.89772	249.1433	220.0	700.9614	1.21784	0.01775
31	0.2990	249.1433	220.0	144.9514	0.35565	0.16070
32	0.2990	233.8807	139.5	144.9514	0.35718	.016070
Parameters of Geothermal Source Stream						
40	brine	315.0		283.0		3.90716
41	brine	311.3304		279.3304		3.90716
42	brine	237.4534		2305.1534		3.90716
43	brine	170.0		138.0		3.90716
Parameters of Air Cooling Stream						
50	air	51.7	14.7	122.3092		91.647
51	air	51.9341	14.72	122.3653		91.647
52	air	73.5463	14.7	127.5636		91.647

[0034] In the system described above, the liquid produced in separator **S1** eventually passes through heat exchanger **HE5** and is partially vaporized. However, the composition of this liquid is only slightly richer than the composition of the liquid separated from the boiling solution in separator **S2.** In general, the richer the composition of the liquid added to the basic solution as compared to the composition of the liquid added to the spent working solution (point **18**), the more efficient the system. In the proposed system, the bulk of liquid from separator **S2**, having parameter as point **15** is throttled to an intermediate pressure, and then divided into vapor and liquid in separator **S3**. As

a result, the liquid stream having the parameters of the point **32** which is mixed with the spent working solution stream having the parameters of the point **18**, is leaner than the liquid separated from the boiling solution in separator **S2**. In addition, the recirculating liquid which is separated in separator **S1** is mixed with the vapor stream from separator **S3**, and, therefore, is enriched. As a result, the liquid stream having the parameters of the point **29**, which is added to the stream of basic solution having the parameters of the point **10**, is richer than the liquid stream produced from separator **S1**.

[0035] If the system is simplified, and the liquid stream from the separator **S2** having parameters of the point **15** is throttled in one step to a pressure equal to the pressure of the stream having the parameters of the point **18**, then the system requires less equipment, but its efficiency is slightly reduced. This simplified, but preferred variant of the system of this invention is shown in Figure 1B, where the separator **S3** and the throttle valve **TV2** have been remove along with the streams having the parameters of the points **30, 31** and **32**. The operation of such a variant of this system of Figure 1A does not require further separate description because all of the remaining features are fully described in conjunction with the detailed description of system and process of Figure 1A.

[0036] If the quantity of liquid from separator **S1** is reduced to such a degree that the composition of the boiling solution stream having the parameters of the point **10** becomes equal to the composition of the working solution which passes through the turbine **T1**, then the separator **S2** can be eliminated along with the throttle valve **TVl**. Therefore, the heat exchanger **HE6** also becomes unnecessary, and is also eliminated because in this implementation there is no risk of liquid droplets being present in the boiling stream due to the absence of the separator **S2**. This even more simplified variant of the system of this invention is presented in Figure 1C. Its efficiency is yet again lower that the efficiency of the previous variant described in Figure 1B, but it is still more efficient than the system described in the prior art.

[0037] The choice in between the three variants of the system of this invention is dictated by economic conditions of operations. One experienced in the art can easily compare the cost of additional equipment, the value of additional power output given by increased efficiency and make an informed decision as to the exact variant chosen.

[0038] A summary of efficiency and performance of these three variants of this invention and the system described in the prior art are presented in Table 2.

TABLE 2
Performance Summary

	Systems of This Invention			Prior Art
	Variant 1	Variant 2	Variant 3	
Heat Input (Btu)	566.5385	565.5725	564.2810	487.5263
Specific Brine Flow (lb/lb)	3.960716	3.9005	3.89159	3.36225
Heat Rejection (Btu)	476.4062	476.4062	476.4062	414.0260
Turbine Enthalpy Drop (Btu)	93.1119	91.7562	90.2988	75.376
Turbine Work (Btu)	90.7841	89.4623	88.0413	73.4828
Pump Work (Btu)	2.9842	2.5812	2.4240	1.867
Air Fan Work (Btu)	5.1414	5.1414	5.1414	3.5888
Net Work (Btu)	82.6785	81.7397	80.4759	68.027
Net Thermal Efficiency (%)	14.595	14.453	14.262	13.954
Second Law efficiency (%)	54.23	53.703	52.995	51.85

[0039] It is apparent from the simulated data in Table 2 that all three variants of this invention show improvements in net values: net work improvements of 21.54%, 20.16% and 18.30%, respectively; and net thermal and second law efficiency improvements of 4.59%, 3.58% and 2.21%, respectively.

[0040] All references cited herein are incorporated herein by reference. While this invention has been described fully and completely, it should be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described. Although the invention has been disclosed with reference to its preferred embodiments, from reading this description those of skill in the art may appreciate changes and modification that may be made which do not depart from the scope and spirit of the invention as described above and claimed hereafter.